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ULTIMATE LOADABILITY IMPROVEMENT BASED ON CONTINGENCY RANKING AND LINE VOLTAGE STABILITY INDEX USING GENETIC ALGORITHM

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ABSTRACT

Due to the exponential growth of the load demand and approach to the installed capacity of the system, power system is exposed to severe operating conditions, causing the system to operate near the critical limits of stability, and it is possible to cause 'out of service' for the whole system.

Voltage stability assessment of the power system is achieved through estimating the loadability margin, at the appropriate time.

The aim of this article is to improve the system's loadability margin without changing the structure of the system by adding any compensating devices or dispread generator. This can be achieved by re-adjusting the control variables of the power system (transformer's tap changing, generator's voltage, Var of shunt injection capacitors and generator active power of PV buses), using genetic algorithm, in order to minimize voltage stability index L_{SR} for the critical line.

Two analysis techniques are adopted to extract the critical line. The first one, based on the maximum value of the line voltage stability index, while the second technique is according to the contingency ranking. The result of the two techniques is identified for extracting the critical line (the most sensitive for increasing the load).

To confirm the effectiveness of the proposed algorithm, an IEEE 6 bus standard system has been tested. The maximum liability can be determined by increasing the total load reactive power until L_{SR} approximate for one.

The results showed an increase in the system's ability to cover the required additional demand load. The program was written in Matlab software by the researchers.

***KEYWORDS:** Loadability Margin, Contingency Ranking, Line Voltage Stability Index & Genetic Algorithm*

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1. INTRODUCTION

The electrical power system is a complex network, which seeks to secure the demand loads according to economic and environmental constraints [1].

The increase of reactive power demand, compared to the total reactive power provided by the system, leads to a negative impact on the system's voltage, i.e. possibility of the instability voltages [2, 3].

Under specific operating condition, the liability limit is known as the ultimate (maximum) load point, while ensuring the continuity of the system's operating within the limits of the stability voltage [3, 4].

Many analytical techniques have been adopted in estimating the liability of the system. [4] Suggests

estimating of liability, based on minimizing the line voltage stability index L_{SR}, which represents the location of the operating point from the critical stability limits, while [5] has offered the impact of line contingency on the maximum margin of liability, also based on minimizing the line voltage stability index, and enhancement of the system's liability through injecting FACTS device-TCSC (i.e. Thyristor Controlled Series Capacitor) with ideal location based on minimizing the voltage stability index [6].

The current article seeks to improve the system's liability to secure the increasing load without any addition of the static compensations, or making any change in the overall structure of the electrical system. The proposed technique based on resetting the control variables (transformer's tap changing, generator's voltage, Var of shunt injection capacitors and generator active power of PV buses) to minimize the voltage stability index VSI for the critical line using Genetic Algorithm GA (approach the optimum value).

The critical line has been diagnosed according to the voltage stability index and the contingency ranking analysis.

2. IMPLEMENTATION OF VOLTAGE STABILITY INDICES

Voltage stability indices are monitoring scalar magnitudes ranging from 0-1. It is a measure of the location of the system's operating point of the critical limits of the stability, under certain load conditions [8].

The line voltage stability index is used to identify the critical lines & weakest buses. Transmission line, which records the highest value of VSI, represents a critical line while bus, which records the lowest maximum value allowed in the demand load, is the weakest bus [7, 9]. When Line VSI getting close to unity, it refers to the maximum possible connected load described as ultimate liability at the nose point in (PV&QV) curves [3].

Previous studies have reviewed many line voltage stability indices that are all participating in three points:

- All indices are calculated according to the analysis of load flow equations.
- All indices are worth between (1) which refers to the collapse voltages and (0) for the case of no-load.
- All Indices of voltage stability can be derived from Simple two bus systems connected through line, then can be extended to n- buses interconnected system [9, 11].

Since the current article is based on the determination of line stability index L_{SR}, the authors present below the derivation of its mathematical formula. hhhrh

L_{SR} which proposed in [8], Consider a two buses system connected through transmission line, that can be extended to an n-line power system is shown in Figure 1.

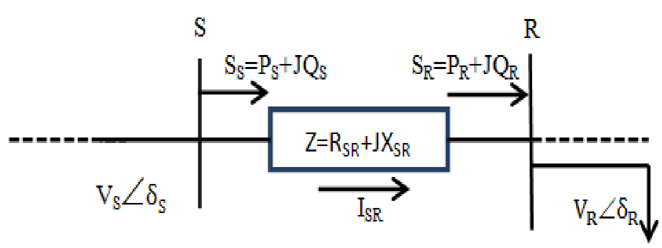

Figure 1: Typical One-Line Diagram of 2 Buses System

Where

S_S, S_R - apparent power for sending and receiving ends buses

V_S, V_R - Voltage at sending and receiving end buses

P_S, P_R - Active power sending end and receiving end buses

Q_S, Q_R - Reactive power for sending end and receiving end buses

δ – Phase shift between sending and the receiving end power.

R_{SR}- Resistance between sending & receiving buses.

X_{SR} - Reactance between sending & receiving buses.

$$I_{Line} = (V_S - V_R)Y_{SR}\llcorner\Theta \quad (1)$$

$$I_{line} = \frac{S_R}{V_R} = \frac{P_R - jQ_R}{V_R\llcorner -\delta_R} \quad (2)$$

$$\frac{S_R}{V_R} = \frac{(V_S - V_R)}{Z\llcorner -\Theta} \quad (3)$$

$$S_R = \frac{V_R(V_S - V_R)}{Z\llcorner -\Theta} \quad (4)$$

$$S_R = \frac{|V_S||V_R|}{Z}\llcorner(\Theta - \delta_S + \delta_R) - \frac{|V_R|^2}{Z}\llcorner\Theta \quad (5)$$

$$S_S = \frac{|V_S|^2}{Z}\llcorner\Theta - \frac{|V_S||V_R|}{Z}\llcorner(\Theta - \delta_S + \delta_R) \quad (6)$$

$$P_R = \frac{|V_S||V_R|}{Z}cos\llcorner(\Theta - \delta) - \frac{|V_R|^2}{Z}cos\Theta \quad (7)$$

$$Q_R = \frac{|V_S||V_R|}{Z}sin\llcorner(\Theta - \delta) - \frac{|V_R|^2}{Z}sin\Theta \quad (8)$$

$$\frac{|V_R|^2}{Z}sin\Theta - \frac{|V_S||V_R|}{Z}sin\llcorner(\Theta - \delta) + \mathrm{Q_R} = 0 \quad (9)$$

$$\frac{sin\Theta}{Z}|V_R|^2 - \frac{|V_S|}{Z}sin\llcorner(\Theta - \delta)|V_R| + \mathrm{Q_R} = \quad (10)$$

$$V_R = \frac{-\mathrm{b} \pm \sqrt{\mathrm{b}^2 - 4\mathrm{ac}}}{2\mathrm{a}}$$

$$V_R = \frac{\frac{|V_S|}{Z}sin\llcorner(\Theta - \delta) \pm \sqrt{\left\{\frac{|V_S|}{Z}sin\llcorner(\Theta - \delta)\right\}^2 - 4\frac{sin\Theta}{Z}.Q_R}}{\frac{2sin\Theta}{Z}} \quad (11)$$

According to the concept of transmission power with maintenance stability in a single line, the discriminator of the voltage quadratic equation should be adjust to be more than or equal to zero, i.e. the solution of this equation at $b^2 - 4\mathrm{ac} \geq 0$

$$\therefore |V_S|sin\llcorner(\Theta - \delta)\}^2 - 4x.Q_R \geq 0 \quad (12)$$

$$\therefore limitation\ is\ L_{\mathrm{SR}} = \frac{4xQ_R}{\{|V_S|sin\llcorner(\Theta - \delta)\}^2} \quad (13)$$

$$L_{SR} = \frac{4xQ_R}{[V_S \sin(\Theta - (\delta_S - \delta_R)]^2} \tag{14}$$

3. ANALYSIS OF LINE FORCED OUTAGE CONTINGENCY

The technique of the contingency ranking can be defined as a pre-condition to forecast the impacts of different contingency situations, such as failure of one or more component (generating units, transformers, transmission lines, etc.). Analysis of the impact of contingency situations is a proactive step, to assist the relevant protection devices in maintaining the security of the system.

In the present article, and to be sure for specifying the critical line, the contingency analysis based on line voltage stability index L_{SR} is used as follows:

- Run the load flow analysis using Newton Raphson method at the half base load, to avoid the out the limit of the stability with removing one line at each time.
- Calculate the L_{SR} for each run of load flow (case) in step a.
- Extract the highest value of L_{SR} for each case.
- Find the critical line for the whole outage lines by comparing the highest value of L_{SR} for each case that determine in step c. The critical line is that appear in most cases [7]

The following flow chart in figure 1 illustrates the detailed steps that are taken by the researchers for improving the loadability of the system to overcome the increase in the load demand, with respect of the critical limit of stability.

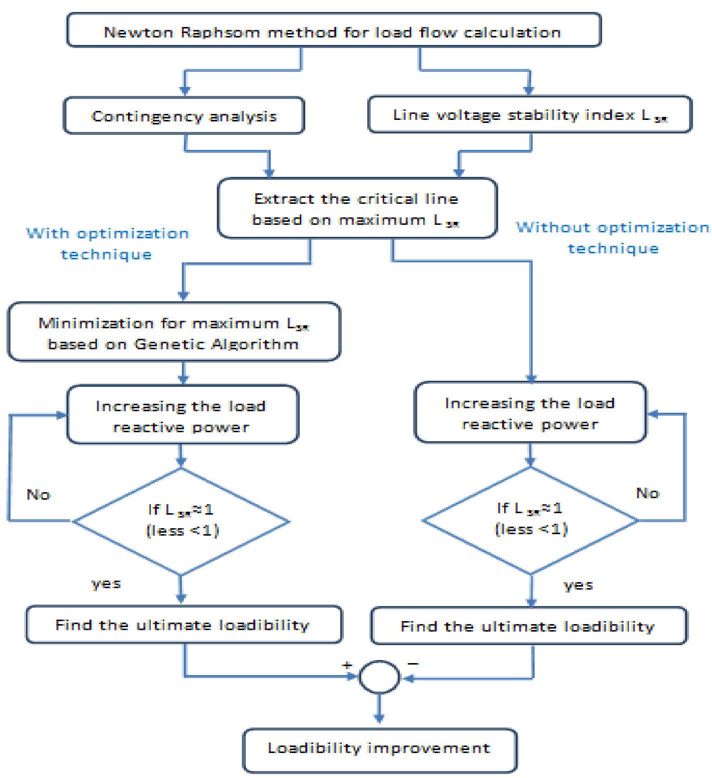

Figure 2: Loadability Improvement

4. INTRODUCTION OF GENETIC ALGORITHM

Genetic algorithm GA is part of the science of artificial intelligence. GA was invented by John Holland in 1960, and developed by his students were, the idea of the algorithm based on Darwin's theory of evolution and natural selection. The principle of the algorithm is survival of the fittest or strongest [12, 13, and 14].

Applications of genetic algorithm are limited on the problems of search and optimization.

4.1 Genetic Algorithm Elements

Despite the differing genetic algorithms by branches of the evolutionary computing, they share at least the following elements:

- **Population of Chromosomes**

This represents the research group or the search space, (a collection of problem solutions). Each chromosome consists of a number of genes (bits). Each chromosome forming the vectors of control variables, while each gene represents the candidate’s solution to a specific problem. Previous Studies varied in coding, not coding and mix between the two for chromosomes of population, which in turn represents the control variable vector. The Studies that have adopted to mix between coding and not coding, resorted to coding the discrete control variable, such as tap changing of the transformer and static compensation device, while it continues as control variable like the voltage of generator leaving without coding [15, 16, 17].

- **Selection**

It is choosing the appropriate chromosomes as "parents" to carry the process of mating with each other. This choice process will not be at random. It depends on the efficiency of the chromosome (objective function) [12].

Many techniques are adopted for selecting the best parents. The Tournament Selection Technique is one of these techniques, which is used in this article.

In this method, three chromosomes in the population have been selected in sequences, and compared at each time. The chromosome, which has best objective function copy itself, instead of the one, which has the worse objective function, remaining the third one without any change.

- **Objective Function (Fitness Function)**

A coefficient for each chromosome gives a certain value, indicating how efficient is chromosome in terms of approaching the best solution? Chromosomes are selected on the basis of the objective function (fitness function).

- **Crossover**

After selecting the appropriate chromosomes from the first generation, gets crossover to format the new chromosomes (offspring), depending on the parent's chromosomes. Crossover represents an interchanging of the genes in each pair of the selected chromosomes (father and mother). [18-20]

- **Mutation**

After the formation of the new offspring, a mutation in the chromosome will be achieved (changes in chromosome's genes), and this helps to improve the characteristics of the children, more than their parents. [21]

Genes change represents a change of control variables with taking into consideration the minimum and maximum allowable values. It reiterates mutation process, and calculates the fitness function of the new chromosomes, even to get the optimum value. Present research focused attention on updating mutation technique, because of their impact in accelerating access to optimum solution; several mechanisms could be adopted in order to carry the process of mutation, such as "gene's inversion, gene duplication, gene deletion, gene insertion and gene's translocation". The five mutation methods, which was mentioned above lead to optimal values at differentiated levels [22-24].

In this article, the proposed genetic algorithm for the current search included a specific mechanism of mutation, depending on the gene's insertion technique [25].

The Specific Mechanism of Mutation has these Steps

- Assuming research population consists of (N) chromosomes and each chromosome in turn includes (n) genes.
- The algorithm picks randomly a set of chromosomes and a group of affiliated genes in the selected chromosomes.
- Let algorithm chooses six randomly chromosomes. As examples (9,5,17,22,13 and 2), configuration of the 9th chromosome is:

Chromosome 9	G1,9	G2,9	G3,9	G4,9	G5,9	G6,9	.	.	Gn,9

- Assume the algorithm chosen randomly a three following gene from the (9^{th}) chromosome to implement the mutation. They are selected (1^{th}, 3^{th}, 8^{th}) genes, and then change its value to another value within the limits of the control variables.

  After the mutation process (9^{th}) chromosomes will be as shown below:

Chromosome 9	**G1,9**	G2,9	**G3,9**	G4,9	G5,9	G6,9	.	.	**Gn,9**

And as for the remaining five chromosomes (5, 17, 22, 13 & 2), others are randomly selected set of genes for each chromosome [25].

The above procedure is generalized to all chromosomes in the population research. A flow chart of the Genetic Algorithm is present in the figure 2

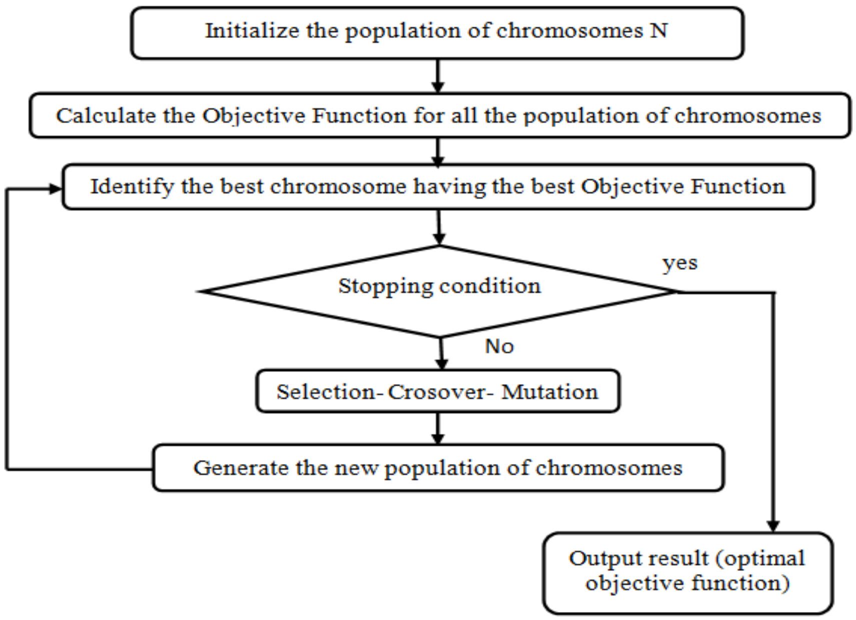

Figure 3: Genetic Algorithm Structure

5. CALCULATION AND RESULTS

In order to explain and implement the analysis of the loadibility improvement in this article, the IEEE 6 bus system is tested for this purpose [26]. Tables 9, 10 and 11 in the Appendix have the data of IEEE 6 bus test system. This system contains 7[th] control variables as follows: two generator voltagesV_{G1}&V_{G2}, two transformers tap changingT_{4-3}&T_{6-5}, two Var shunt injection capacitance Q_{C4} &Q_{C6}And one generator active power of PV bus P_{G2} as shown in Figure 3

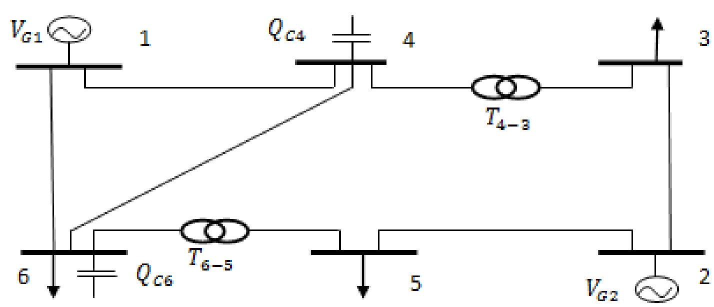

Figure 4: IEEE 6 Bus Test System

5.1 The Steps of the Proposed Algorithm

- Based on the result of the load flow analysis (Newton Raphson method), the line voltage stability index L_{SR} in eq. 14 has been calculated. The system IEEE 6 bus has 7 lines. Table 1 shows the rank of L_{SR} for each line, where the line (5-2) is the critical line (weakness one), which has the highest value of L_{SR} = 0.7704 (Rank 1).
- According to the contingency analysis based on line voltage stability index L_{SR}, Table 2 shows the rank of L_{SR} of each case of outage line. By comparing the value of higher L_{SR} of for each case of outage line, Table 3 show that line (5-2) is the critical line of the whole system (IEEE 6 bus), because when removing the line (5-2), the highest value of the index L_{SR} appear >1 (L_{SR} = 3.2461) for the line (2-3) and this is out of stability limit. Although the

line (5-2) has the highest value of $L_{SR,}$ for many cases, line outage is rather than line 2-3 as shown in Table 3. According to the liner stability index L_{SR} in Table 1 and contingency analysis in Tables 2 & 3, the line (5-2) is the most important line (the critical line) that must be minimized using GA

Table 1: The Line Voltage Stability Index L_{SR} of IEEE 6 Bus

Rank	Lines	L_{SR}
1	5-2	0.7704
2	2-3	0.4674
3	1-4	0.1639
4	1-6	0.1458
5	6-5	0.0389
6	4-3	0.0331
7	4-6	0.0317

Table 2: The L_{SR} for Each Case of Line Outage

Line Outage	1-6		1-4		4-6		5-2	
Rank	Lines	L_{SR}	Lines	L_{SR}	Lines	L_{SR}	Lines	L_{SR}
1	5-2	0.4440	5-2	0.4204	5-2	0.3358	2-3	3.2461 (out)
2	2-3	0.2427	2-3	0.2540	2-3	0.1191	1-4	0.3253
3	1-4	0.1042	1-6	0.1241	1-6	0.1185	1-6	0.2973
4	4-6	0.0600	4-6	0.0610	1-4	0.0704	4-3	0.1288
5	4-3	0.0149	4-3	0.0168	6-5	0.0338	6-5	0.1234
6	6-5	0.0050	6-5	0.0030	4-3	0.0241	4-6	0.0285

Con. Table 2

Line Outage	2-3		6-5		4-3	
Rank	Lines	L_{SR}	Lines	L_{SR}	Lines	L_{SR}
1	5-2	0.4311	2-3	0.6488	2-3	0.8002
2	1-6	0.2263	5-2	0.3199	5-2	0.4441
3	1-4	0.1697	1-4	0.1549	6-5	0.0532
4	6-5	0.1144	1-6	0.1068	1-6	0.0235
5	4-6	0.0603	4-3	0.0683	4-6	0.0095
6	4-3	0.0354	4-6	0.0470	1-4	0.0040

Table 3: The L_{SR} of the Critical Line for Each Outage Line

Line Outage	The Critical Line	L_{SR}
1 (1-6)	5-2	0.4440
2 (1-4)	5-2	0.4204
3 (4-6)	5-2	0.3358
4 (5-2)	2-3	3.2461 (out of stability limit >1)
5 (2-3)	5-2	0.4311
6 (6-5)	2-3	0.6488
7 (4-3)	2-3	0.8002

- Genetic Algorithm GA minimized the value of L_{SR} for the line critical line (5-2) in IEEE 6 bus from the initial value (L_{SR} = 0.7704) to optimal value (L_{SR}=0. 2136) by optimizing the values of the control variables, as shown in Table 4. Table 5 shows the objective function (line voltage stability index L_{SR}) before and after the optimization technique using Genetic Algorithm at the base loadibilty ($Q_L = 36$ Mvar). This Table also shows that the lines (1-6) and (5-2) are the most important lines, which have the highest value of L_{SR} (critical line). Figure 4 shows the L_{SR} of the critical line of the IEEE 6 bus using GA for 50 iterations. Figure 5 shows L_{SR} of IEEE 6 bus with and without using GA.

Table 4: Initial and Optimal Control Variables with its Objective Function

Control Variables	Initial	Optimal
Generator voltage V_{G1}	1.050	1.1
Generator voltage V_{G2}	1.100	1.1353
Transformer tap changing T_{6-5}	1.025	0.9092
Transformer tap changing T_{4-3}	1.100	1.0334
Var of shunt injection capacitance Q_{C4}	0.000	4.9157
Var of shunt injection capacitance Q_{C6}	0.000	5.1402
Generator active power of PV bus P_{G2}	50.00	50.0211
Line voltage stability index (L_{SR})	0.7704	0.2136

Table 5: The L_{SR} Before and After Genetic Algorithm Optimization Technique

Rank	Before Optimization at Base Loadibility Q_L = 36 Mvar		After Optimization at Based Loadibility Q_L = 36 Mvar	
	Lines	Line VSI	Lines	Line VSI
1	2-5	0.7704	1-6	0.2136
2	2-3	0.4674	2-5	0.2133
3	1-4	0.1639	6-5	0.1853
4	1-6	0.1458	2-3	0.1849
5	6-5	0.0389	1-4	0.1757
6	4-3	0.0331	4-6	0.0822
7	4-6	0.0317	4-3	0.0530

- The present article depends on increasing the reactive power of the load to specify the loadibility margin. The proposed algorithm increases the load reactive power from the base case (Q_L = 36 Mvar) until L_{SR} reaches the critical value (closes to 1). In this case L_{SR} =0.9995 and Q_L =47.376 Mvar, and this is the ultimate loadibilty of the base load before optimization technique. The critical line is still (5-2).
- At the value of ultimate loadibility Q_L =47.376 Mvar of the base load: The proposed algorithm calculates the line voltage stability index according to the genetic algorithm optimization technique. The genetic algorithm reduces the critical value of L_{SR} from 0.9995 to 0.3448 (far from the risk region) with critical line of (5-2).
- In order to specify the ultimate loadibility after optimization technique based on GA, the proposed algorithm increases the load reactive power until L_{SR} reaches the critical value (closes to one)). In this case L_{SR} = 0.9997 and the ultimate loadibility Q_L =84.15 Mvar and the critical line is (5-2), as also shown in Table 6. Genetic Algorithm improves the ultimate loadbility by 43.71%, and the voltage stability index L_{SR} of the critical line by 72.27 %, as shown in Table 7.

Table 6: Ultimate Loadibility Before and After Optimization Technique

Rank	Before Optimization at Ultimate Loadibility Q_L =47.376 Mvar		After Optimization at Loadibility Q_L =47.376 Mvar		After Optimization at Ultimate Loadibility Q_L =84.15 Mvar	
1	5-2	0.9995	5-2	0.3448	5-2	0.9997
2	2-3	0.5483	2-3	0.2713	2-3	0.5511
3	1-4	0.2227	1-6	0.2711	1-6	0.4657
4	1-6	0.2186	1-4	0.2238	1-4	0.3882
5	6-5	0.0725	6-5	0.2142	6-5	0.3297
6	4-3	0.0505	4-6	0.0960	4-6	0.1530
7	4-6	0.0488	4-3	0.0686	4-3	0.1264

Table 7: Improvement of Ultimate Loadibility and L_{SR} Based on GA

	Initial Case	Optimal Case	Improvement
Ultimate loadibilty	47.376 Mvar	84.15 Mvar	43.71 %
$L_{SR}$of the critical line	0.7704	0.2136	72.27 %

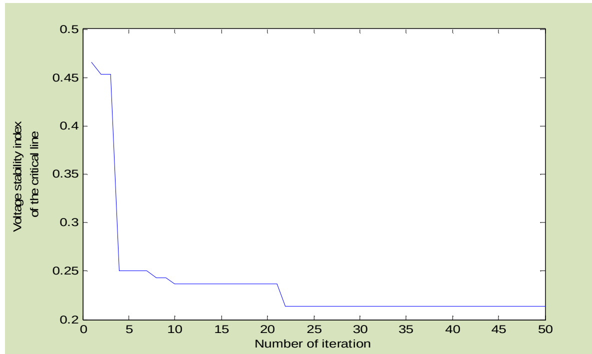

Figure 5: The Voltage Stability Index of the Critical Line for IEEE 6 Bus Using GA

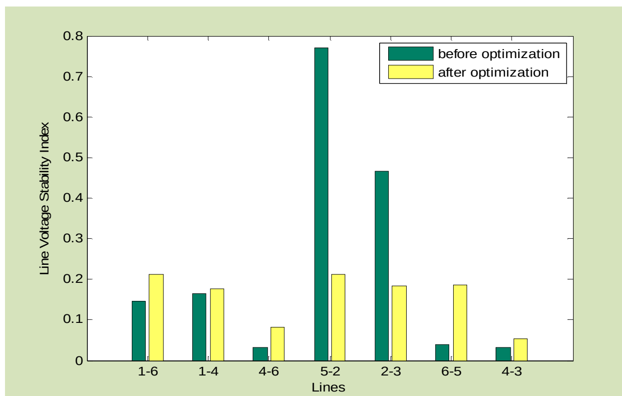

Figure 6: The Line Voltage Stability Index for IEEE 6 Bus with and without GA

CONCLUSIONS

The loadability improvement in this article can be achieved according to the minimized voltage stability index L_{SR} for the critical line, by re-adjusting the control variable of the system. Genetic Algorithm GA has been adopted for this purpose. The contingency ranking enhancement of the line voltage stability indexes to identify the critical line. The ultimate loadability can be determined by increasing the total load reactive power until L_{SR} closes to one (critical point of voltage stability limit). The results of IEEE 6 bus test system show that, GA improves the loadability margin and the voltage stability index for the critical line by 43.71% and 72.27%, respectively. The software implemented by the researchers is based on Matlab.

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APPENDICES

Data of IEEE 6 Bus Test System [26]

Table A.1: Line Data of IEEE 6 Bus

Line No.	From Bus	To Bus	Branch Impedance p.u	Transformer Tap
1	1	6	0.123+j0.518	1
2	1	4	0.080+j0.370	1
3	4	6	0.097+j0.407	1
4	5	2	0.282+j0.640	1
5	2	3	0.723+j1.050	1
6	6	5	0.000+j0.300	1.025
7	4	3	0.000+j0.133	1.100

Table A.2: Bus Data of IEEE 6 Bus

Bus No.	Bus Type	Bus Voltage	Angle Degree	Load		Generator		Q_C
				P_L	Q_L	P_G	Q_G	
1	Slack	1.05	0	0	0	0	0	0
2	PU	1.10	0	0	0	50	0	0
3	PQ	1	0	55	13	0	0	0
4	PQ	1	0	0	0	0	0	0
5	PQ	1	0	30	18	0	0	0
6	PQ	1	0	50	5	0	0	0

Table A.3: Control Variable Constraints of IEEE 6 Bus

	No. of Control Variable	Control Variable	Min. Limit	Max. Limit	Initial Value
Generator voltage	1	V_{G1}	1.00	1.10	1.050
	2	V_{G2}	1.10	1.15	1.100
Transformer Tap changing	3	T_{5-6}	0.90	1.1	1.025
	4	T_{4-3}	0.90	1.1	1.100
Shunt injection capacitance	5	Q_{c4}	0	5	0.000
	6	Q_{c6}	0	5.5	0.000
Generator active power	7	P_{G2}	10	100	50